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Abstract

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Keywords

amirante, management, coastal, infrastructure, islands, data, seychelles, spatial, development, GeoQUEST

Disciplines

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Development of a Spatial Data Infrastructure for coastal management in the Amirante Islands, Seychelles

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Spatial data infrastructures play a key role in coastal management decision making in the Seychelles. This paper describes four components of a web-based spatial data infrastructure that was developed to facilitate coastal management of the Amirante Islands in the Seychelles. The four components include *i)* the institutional arrangement for using spatial data effectively to address local management challenges, *ii)* the production of island habitat maps from remotely sensed data, *iii)* the tasks undertaken for promoting access to and use of this spatial data, and *iv)* an example of how this data is used for a specific coastal management application in the Seychelles is provided. By outlining these four components, the value of this spatial data infrastructure framework for tropical coastal management in the Seychelles is demonstrated.

Keywords: Seychelles, remote sensing, spatial data infrastructure

Introduction: Spatial data infrastructures as a marine resource management tool

The coastal zone extends both seawards and landwards of the coastline to limits that are determined by the geographical range of the natural processes and human activities that take place there. An approximate range in tropical latitudes may be from 200 m depth on the seaward margin to the inland limits of coastal plains (Craik *et al.*, 1995). Integrated coastal zone management (ICZM) aims to make anthropogenic demands on natural coastal systems compatible with ecological needs through allocation of environmental, socio-cultural and institutional resources to achieve the sustainable multiple use of the coastal zone (Clark *et al.*, 1977). A paradigm shift may be occurring in the role of coastal scientists from observers of the natural world to partners in the quest for answers to pressing questions related to sustainable management and conservation of marine resources (Crosby *et al*., 2002). This shift can partly be attributed to the increased uptake of Geographical Information System (GIS), which has improved coastal management decision making over the last thirty years by facilitating a structured approach to the management of coastal common pool resources (Ostrom, 1990).

A GIS is a system that encompasses computer hardware, specialised software and personnel with spatial analysis expertise for storing, querying, analyzing and displaying geographically referenced information (Burrough and McDonnell, 1998). Increased uptake of GIS is underpinned by a growing awareness of how to manipulate large amounts of spatial information efficiently: increased connectivity of networks that allow data to be shared and standardization between database and computer programs (Burrough and McDonnell, 1998). Geospatial data typically consist of spatially referenced records that store information on the attributes of entities and their relationships to other records held. The ability to compute relationships between objects based on standard geometric calculations (area, perimeter length) and to generate new objects on request by performing simple tasks enables the spatial component of data to become key to analysis. Such analysis is distinguished from cartography by its dynamicity and analytical content. While traditional maps present a static picture of phenomena and their relationships at one point in time, a GIS transforms map data into customized information. The emphasis of this customization is moving increasingly toward spatial enquiry that supports decision making for coastal managers (Mumby *et al.*, 1995).

Remote sensing instruments provide a synoptic portrait of the earth's surface by recording numerical information on the radiance measured from a series of picture elements (pixels) across a number of spectral bands, i.e. within discrete wavelength portions of the electromagnetic spectrum (Green *et al*., 2000). Broad scale coral reef habitat mapping is usually undertaken from a satellite or airborne platform. Passive instruments focus sunlight reflected off the earth's surface onto a detector to create an electronic response, which is digitally recorded in a gridded pixel array. Since the launch of the first earth observation satellites in the 1970s, sensor capability for mapping in shallow tropical environments has become well established (for a review, see Mumby *et al*., 1997). The accurate discrimination of reef communities depends on the spatial and spectral resolution of the sensor used. Several well-placed, narrow (10 nm) spectral bands can detect subtle differences in reflectance between reef communities, e.g. seagrass vs. coral. Mapping benthic assemblages on coral reefs therefore requires a band combination that emphasises distinct spectral differences between different components of coastal communities that are apparent at wavelengths in the visible section of the electromagnetic spectrum (400 – 700 nm). Image pre-processing techniques that facilitate interpretation of features on the seabed include correction for the effects of the atmosphere on light transfer, correction for the scattering and absorptive effects of the water column on light and the removal of light directly reflected off the water surface, or glint (Green *et al*., 2000). Once these confounding issues have been addressed, remotely sensed imagery can be accurately classified into coastal habitat maps.

A spatial data infrastructure (SDI) brings together geoinformation such as habitat maps derived from remotely sensed imagery for use in management decision-making. This is commonly achieved using an online data portal featuring a metadata catalogue with descriptions of available data sets and imagery, which links many networked servers distributed over a large geographic area and enables users may to visually browse and query data or build online maps within the portal (Wright, 2009). The overriding objective of SDIs is to facilitate access to geographic information that is held by a wide range of stakeholders with a view to maximizing overall usage. Although substantial financial investments are made in the collection of geographic information through fieldwork and technologies, such as remote sensing, it often seems that the biggest challenge is the translation of this knowledge into useful and effective decision-making through further integration into a SDI. As many land administration systems have traditionally only focused on land and have stopped at high water mark, SDIs have also typically only related to land (Williamson et al. 2001). To illustrate utility of this framework for tropical coastal management, the four components of SDI development and implementation are described, including: *i.* the institutional arrangements that are required for delivering geographic information, *ii.* tasks related to the creation and maintenance of fundamental datasets, *iii.* procedures for making geographic information accessible, and *iv.* ways of facilitating the development of strategic technology and applications (Masser, 2007).

Coastal management in the Seychelles: Institutional arrangements for spatial data management

The Seychelles archipelago is comprised of 115 islands and islets located in the western Indian Ocean, which can be classed into seven main groups according to their location and the banks on which they sit. The Inner Islands, Coetivy/Platte, Amirantes and Alphonse/St. Francois groups are found in the northeast of the Seychelles Exclusive Economic Zone (EEZ), whereas the Aldabra, Farquhar and Cosmoledo group is to the southwest. The Inner Island group contains all of Seychelles' 41 granitic islands (plus two coralline islands, the most northerly of the archipelago), while the remaining 74 Outer Islands are of coralline origin and are composed of low sand cays and elevated reefs limestones (Shah, 1995). Given the aforementioned coastal zone definition, which spans from 200 m water depth to the limit of the coastal plains, almost the entirety of the Seychelles can be considered a contiguous coastal zone due to the islands' small size (Shah, 1995).

Coastal zone management in the Seychelles dates back to the creation of the Nature Conservation Board in the 1960s, with administrative responsibility transferring to the Ministry of Environment following its creation in 1989 (Shah, 1997). Responsibility for contemporary coastal zone management lies with a number of affiliated institutions, comprised of several government departments, including the Department of Environment (in particular, the Environmental Engineering and Waterways Section), the Department of Land Use and Habitat and affiliated organisations responsible for island management, including the Seychelles Centre for Marine Research and Technology (SCMRT), Seychelles Islands Foundation and the Island Development Company. Collectively, these affiliated organisations have been granted, or have purchased, islands for the purpose of conservation, while a number of private tourism companies have purchased islands and incorporated coastal zone management into their eco-tourism initiatives. The majority of Seychelles' outer islands are managed by the Island Development Company, which has

been responsible for agricultural development in the past, but now works alongside the Department of Environment on a range of conservation projects. The degree to which integrated coastal zone management is undertaken on the individual islands of the Seychelles varies; however, the various agencies work collaboratively for the sustainable use and distribution of coastal resources and are bound by the same legislation.
On the inner granitic islands, which have a steep, mountainous inner topography, resident populations and visitors need to be accommodated within the confines of a narrow coastal strip, which intensifies the challenges of effective coastal zone management. Some of the issues that need to be addressed on the inner islands include sewage waste management, urbanisation, coastal tourism development, industrial development, surface pollution run-off, offshore land reclamation, wetland reclamation and the threat of over-fishing. Although similar challenges are present on the outer islands, their effects are less intense because of smaller resident populations, relative remoteness and comparatively strict planning regulations, thus, these challenges can be more easily addressed.

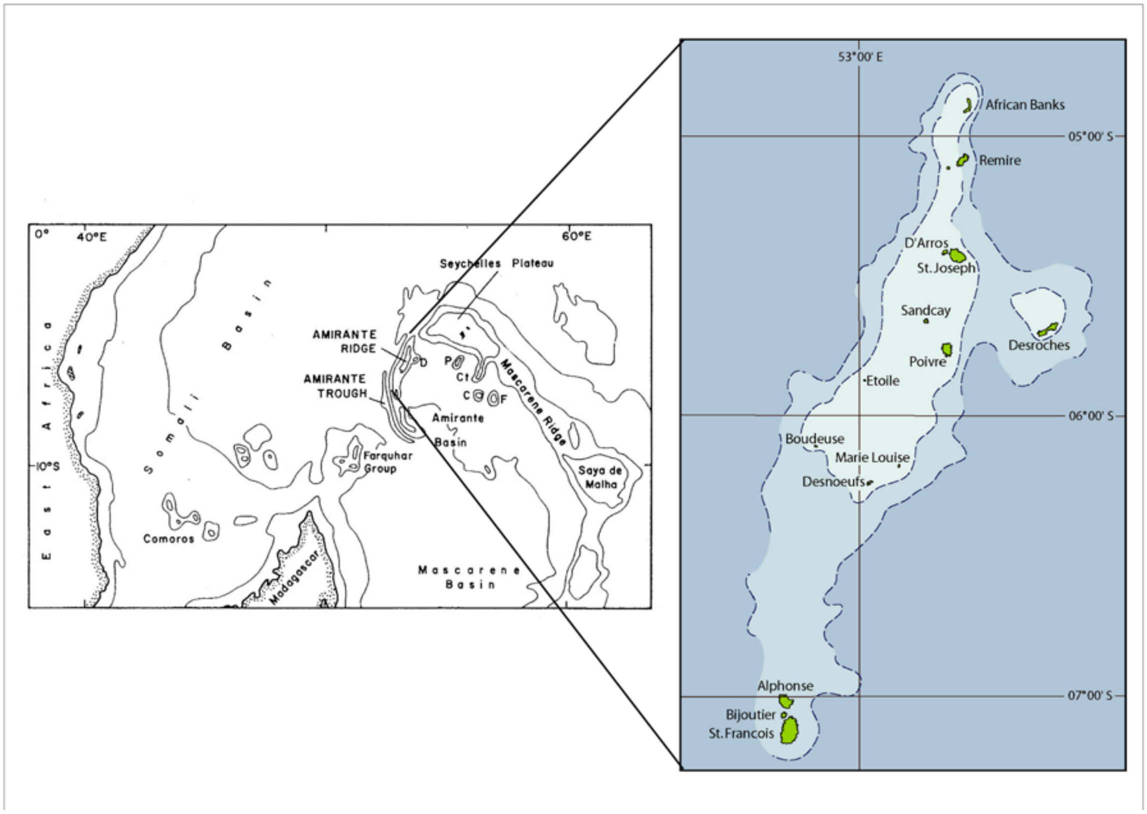
By contrast, the Amirantes play host to a thriving tourism industry, which has seen development of hotels and their associated infrastructure. Management issues to be addressed here include waste management, due to the lack of landfill facilities, the logistical difficulties of waste disposal and the adequate transport and storage of fuel. A common challenge to management of the coral reefs of both the inner and outer islands is presented by the threat of a recurrence of the 1998 coral bleaching event. This episode occurred due to a perturbation of the standard annual cycle of Indian Ocean warming in which reduced surface current circulation caused regional sea surface temperatures to exhibit anomalies of greater than 1°C above their upper threshold for an extended period (from November 1997 to April 1998). While reefs have shown signs of recovery in terms of live coral cover following this event, ongoing monitoring is required to track recovery and manage potential future bleaching episodes.

Since the introduction of GIS and remote sensing technologies to Seychelles in the early '90s, habitat maps derived from remotely sensed imagery are increasingly being used as primary information sources for coastal management. For example, the Centre for GIS of the Ministry of National Development and the GIS and Data Management Unit of the Department of Environment produced a digital *Coastal Sensitivity Atlas* for the Seychelles under the National Oil Spill Contingency Plan of Seychelles. While adequate information in the form of aerial orthophotos was available to meet this mandate for the inner granitic islands, the only information available for the outer coralline islands was a set of charts produced for the government of Seychelles between 1959 and 1961 by the UK Ordnance Survey (OS) and Directorate of Overseas Surveys (DOS). These are the only charts available for the outer islands and, while the georeferencing associated with these outer islands charts was stated to be approximate, the locational displacement was later found to range between 100 m – 250 m both in latitude and longitude for most of the islands. More recently, these charts have been superseded by a set of aerial orthophotos, captured in 1998/99, predominantly covering the three main inhabited islands of the Seychelles and their accompanying satellite islands. Although the use of remotely sensed data has been limited for the outer islands, it is also becoming increasingly popular in recent years due to the realisation that, despite the relatively high cost of the images, it is still a cheaper option than undertaking traditional mapping methods over such a geographically dispersed group of islands and provides high quality results. Finally, the

Seychelles' Clearing House Mechanism stores national scale metadata of coastal and marine environment information, from which coastal datasets can be accessed.

Field Site: The Amirante Islands, Seychelles

The Amirantes archipelago comprises a group of carbonate islands and islets extending over a distance of ~152 km, from 04°52'S (African Banks) to 06°14'S (Desnoeufs) (Figure 1). The majority of the islands are sea level coral reef platforms with varying degrees of subaerial sand cay and coral island development. They have evolved over the last 6,000 years as post-glacial sea level has approached its present level in the region (Stoddart, 1984). The Amirantes Bank is an elongate structure, measuring approximately 180 km by 35 km, deepest in its central zone (up to – 70 m) with a marginal rim at water depths of 11 to 27 m. Approximately 95 km further south are the atolls of Alphonse and Bijoutier / St. François, which form the Alphonse Group. Of the 14 islands, 13 were mapped, the exception being Desroches, a shallow submerged atoll, 19-21 km in diameter, lying 16 km to the east of the Amirante Bank.



[**Figure 1.** Regional geological setting of the Amirantes Ridge, western Indian Ocean (left) and the islands of the Amirantes Archipelago (right), approximate bathymetric contours = 1 km and 4 km. (Adapted from Spencer *et al*., 2009).]

Materials and Methods: Mapping the Amirante Islands using remote sensing techniques

A collaborative expedition was conducted to the Amirante Bank between the Seychelles Government Department of Environment, Cambridge Coastal Research Unit, Cambridge University, UK and the Khaled bin Sultan Living Oceans Foundation (LOF) onboard *M.Y. Golden Shadow*, from 10th – 28th January 2005. The primary aim was to use a Compact Airborne Spectrographic Imager (CASI) sensor onboard the seaplane Golden Eye to conduct large-scale mapping of the reefs and islands of the southern Amirantes. The areas selected for survey were large and, thus, not amenable to detailed ground mapping over a relatively short field visit. However, the sites were ideally suited to airborne mapping using a CASI sensor onboard a seaplane. A field campaign was run alongside the airborne surveys. Data records were collected on the terrestrial and marine habitats present. Results from the CASI image processing provided the first detailed maps of the distribution of shallow marine habitats for each of these locations.

Airborne remote sensing surveys

Data were recorded over the 430-850 nm region of the electromagnetic spectrum using a CASI sensor. The sensor was calibrated to measure radiance in 19 spectral bands at a pixel size of 1 m^2. Synoptic coverage was acquired by following a predetermined set of flight lines over each island at an altitude of 1000 m. This generated a series of adjacent flight lines, each of width 512 m, which could be geocorrected with reference to each other and processed into habitat maps.

Ground-referencing surveys

Ground-referencing was conducted in both terrestrial and marine environments. On land and underwater, positions were measured with a GPS unit (horizontal accuracy of ±10 m) and the island habitat represented at that position was recorded. Over 1,500 records of ground-reference points were collected. In deep water, quantitative underwater surveys were conducted using well-established video transect methods (English *et al.*, 1997). In shallow water, ground-referencing was conducted from the surface by lowering a glass-bottomed bucket over the side of a small boat which was driven towards the beach along a line perpendicular to the coastline from a start point of water depth ca. 20 m. The boat moved at a constant speed and at one minute intervals the substrate type and position were recorded. Terrestrial surveys encompassed beach profiles, vegetation surveys, sediment samples, soil samples, collections of insects and observations of plant and bird life.

Processing of the remotely sensed imagery to generate habitat maps

Prior to classification, a number of pre-processing routines were applied to the data. Raw data were geocorrected using ground control points and flight strips were mosaiced into a single image for each island. Correction for the effects of scattering and absorption in the atmosphere was performed using the Atmospheric Correction Now (ACORN) algorithm to retrieve radiance values at the water surface (ACORN, 2001). The method devised by Lyzenga (1981) was used for band-wise correction of the effects of absorption and scattering in the water column. This assumed that the vertical radiative transfer through the water column could be approximated to a logarithmic decrease in radiation with increasing depth. The output of this was a series of depth invariant bands upon which an image classification could be performed.

A maximum likelihood classification was used to assign each pixel of the image to the most likely thematic class on the basis of statistical probability (Mather, 2004). This supervised classification required the user to define training sets of both terrestrial and benthic coverages in a number of pixels where the content had been verified in the field. A statistical population of reflectance values was built up by these training sets for each island habitat class in feature space. As a parametric classifier, the maximum likelihood function assumes that each thematic sample category can be represented by a Gaussian probability density function derived from the radiance across each spectral band. Given the user-specified training signatures, it is possible to compute the statistical probability of a pixel being a member of each thematic spectral class (Thomas *et al*., 1987).

Classification accuracy was assessed with field data collected *in situ.* Patches from the individual island habitat maps were randomly selected and their centroid coordinates were exported into a GPS. These locations were visited in the field and the habitat type at each location was recorded. Validation data were compared against the habitat class assigned by the map and labelled either correct if they were found to be the same, or incorrect if different. Overall accuracy was expressed as the proportion of patches assessed that was found to be correct (Congalton, 1991). Such an approach encompassed both locational and thematic aspects of accuracy and for the 14 island maps developed, accuracies ranged from 72-87% (Hamylton et al. 2010).

At the regional scale, individual island habitat map keys were combined to produce an overall scheme for the Amirante Islands. This hierarchical scheme incorporated 28 habitat classes in total, with 15 classes in the first tier and 13 in the second (Table 1).

First tier	Second tier
1. Terrestrial vegetation: trees and shrubs	1.1 Coconut woodland 1.2 Other trees and shrubs
2. Herbs and grasses 3. Saline pond 4. Cleared/ bare ground 5. Littoral hedge 6. Mangrove woodland	
7. Coarse beach material & rocks	7.1 Coral sandstone/ Raised reef 7.2 Coral boulders 7.3 Beachrock
8. Beach sand 9. Rock pavement 10. Reef-flat sand	
11. Seagrass	11.1 Low density seagrass/ macroalgae 11.2 Medium density seagrass 11.3 High density seagrass
12. Lagoon patch reef 13. Lagoon sand	
14. Fore-reef slope material or structure. Not sand.	14.1 Coral rubble with coralline algae 14.2 Fore-reef slope coral spurs with coralline algae 14.3 Rocky fore-reef slope 14.4 Fore-reef slope rubble and sand 14.5 Fore-reef slope with coral
15. Fore-reef slope sand	

Table 1. Two-tier classification scheme for the marine habitats of the Amirante Islands

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Making geoinformation accessible in the Seychelles

The island habitat maps were published hardcopy format as an A1 Atlas (Spencer et al. 2009) and distributed to coastal management personnel in the Seychelles, including staff from government departments, private sector organisations, non-governmental organisations and independent researchers. In October 2007, a launch event was held for this Atlas in Victoria, Seychelles. In association with this event, a week-long training workshop on coastal remote sensing and GIS was provided by Cambridge Coastal Research Unit and the Department of Environment, Seychelles. This workshop was attended by 15 members of staff from different coastal management organisations in the Seychelles. Topics included processing and classification of remotely sensed imagery to produce habitat maps and analysis of habitat maps using geospatial techniques. All activities were undertaken using freely available WinBilko software and several lessons drew on the content of the associated manual on *Applications of Satellite and Airborne Image Data to Coastal Management* (UNESCO, 1999).

A data portal can be defined as an internet environment featuring a metadata catalogue with descriptions of available data sets and imagery, which links many networked servers distributed over a large geographic areas and enables users to visually browse and query data or build online maps within the portal (Wright, 2009). The Living Oceans Foundation (LOF) developed a GIS Data Portal to make the digital habitat maps available through a web-based interface (Gayanilo and Williams, 2009), which was hosted on LOF's website (see GIS Data Portal at www.livingoceansfoundation.org). Within the GIS Data Portal, a Seychelles Viewer application was built in conjunction with the Centre for GIS (CGIS) at Towson University, Maryland, for the Amirante Island habitat maps. The application was designed using a combination of Flex Builder 3, which is an Adobe open source framework for building expressive web applications, along with several ArcGIS 9.3 applications (ArcCatalog, ArcMap ArcServer and ArcSDE). Visual design and tools, including a unique habitat reporting tool written for assessing change over time, were scripted by CGIS using Flex.

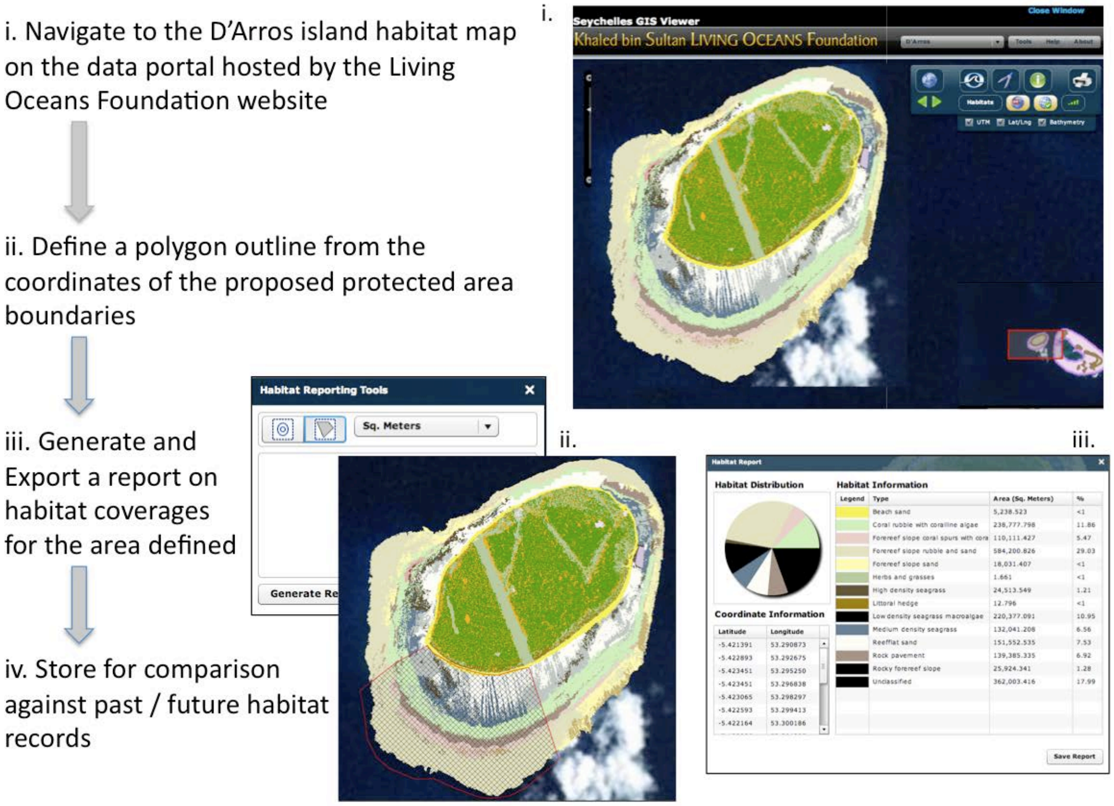
The interactive map viewer provided a scalable platform that facilitated access to the Amirantes habitat maps. Each map could be navigated across a range of scales and a set of key analytical tools encompassing navigation, interrogation and reporting functions was provided. Bathymetry derived from the General Bathymetric Chart of the Oceans 08 Grid, which is a global 30 arc-second grid, and both UTM and latitude/longitude grids was also incorporated. Navigation functions included the ability to select specific islands where available spatial data could be viewed, a scale bar to control zoom extent, and panning tools to enable users to view different geographical areas of the dataset. The Habitat legend featured high-resolution photographic records of each habitat type for reference. Interrogation functions included measurement tools for both one-dimensional linear distances and two-dimensional areas and a function to identify the habitat type recorded at any point location selected on the map. Reporting tools allowed an area to be outlined using either radius or polygon definition tools for which an automated "habitat report" could be generated. This report detailed habitat types; a map of the query areas and specific coordinate information for the area defined and could be exported as a separate portable document format (PDF) file.

Utility of the Spatial Data Infrastructure for coastal management

A key aim of this paper is to demonstrate the practical utility of the Amirantes web viewer and associated analysis tools for coastal management. An example is therefore provided in which the area of different classes of benthic coverage (habitat types) was computed for a user-specified geographical region. This was applied by the D'Arros Island Marine Resource Manager for a marine protected area for conservation at D'Arros Island in the northern Amirantes (05°25'S; 53°17'E). The purpose of the exercise was to assess change within the protected area by carrying out a comparison against benthic community assessments that had previously been conducted (Engelhardt, 2002).

Habitat types were selected by location on the basis of their meeting the logical criterion that they were “contained within” the D’Arros Island Protected Area boundary delineated using the polygon definition tool. Following selection, the area of each digitally represented polygon was measured iteratively using an algorithm that proceeded by polygon subdivision into trapezia and subsequent calculation of area from a two dimensional space defined around the polygon (Longley *et al*., 2005). The relative areas of each habitat class were then illustrated graphically using the reporting tool. Such reports can then be exported, and stored separately, with both raw data and graphical illustrations generated from these available for comparison with past and future figures for monitoring change.

Figure 2 illustrates how a series of simple spatial analysis operations can be combined to produce a discrete dataset, the attributes of which can be analyzed separately and displayed using the charts. These can also be stored as an instantaneous record of the habitats falling within a given area, against which comparisons can be drawn at a later stage to assess change. Such functionality is particularly valuable for conservation management purposes, where there is a need to monitor the performance of protected areas on an ongoing basis. The wide-ranging applicability and value of this functionality was demonstrated in a survey of 60 coastal managers and end users around the world who identified detection of coastal habitat change as the primary management application of remote sensing (Mumby and Edwards, 2000).



[Figure 2 Use of the web-based spatial data infrastructure tools to generate a report of different habitat types in D'Arros Island Marine Protected Area**.]**

Conclusions and lessons to be learned for other case study sites

The example presented here demonstrates that spatial data infrastructures are more than a central repository for information: they have an important role in providing access to spatial data and associated tools to facilitate analysis that is relevant to management planning for coastal systems. While the development of GIS databases has been described for tropical coastal management (Mumby *et al.*, 1995, Turner and Chapman, 2004), the scope of a spatial data infrastructure extends beyond database development to storage and provision of this data in a user-friendly manner through the internet. The presence of a data viewer with tools that enable the user to both view and interrogate spatial datasets obviates the need to own GIS software licenses or hardware for data storage, opening up analysis opportunities to a wider range of potential users. In this sense, recent developments in web-based applications represent an important step in the growth of geospatial tools for coastal management.

By considering each of the four components of spatial data infrastructure development, a wider scope of operation is emphasised. This scope extends beyond the accumulation and storage of spatial information as a coastal management tool to consider human resources, such as development of spatial analysis and remote sensing skills through provision of training for staff from management authorities and provision of the technical means for analysis to be carried out through a web-based data viewer. By adopting this wider scope in the form of a spatial data infrastructure, spatial data can be used effectively for coastal management in a practical manner.

Marine management is a dynamic process built on a changing knowledge of resource status. Periodic revisions of the information held within the GIS are therefore essential to the maintenance of effective management regimes, the frequency of which will be dependent on the rate at which the coastal systems themselves vary, ranging from annual to decadal intervals, with the inherent requirement that surveys themselves are comparable (i.e. they adopt consistent, or at least compatible, classification schemes) (English et al. 1997). Furthermore, a GIS is only as good as the information it hosts and aspects of data quality such as resolution, completeness, precision and accuracy need to be considered. In these terms, the remotely sensed imagery employed in this study was fit for purpose for developing a series of habitat maps of the remote and spatially extensive Amirante Islands that formed the basis of a coastal management spatial data infrastructure. However, to conduct ongoing management of coastal resources, repeat acquisitions of remotely sensed imagery are necessary and the wider scope of operation of an SDI emphasised by this study highlights some of the institutional arrangements required to truly integrate datasets of this nature into the coastal management process. Such integration also requires ongoing investment in maintaining and updating online portals as new information becomes available in the form of trained website developers.

Finally, it is worth noting that coastal SDIs do not exist in isolation from broader regional, national, and global initiatives (Bartlett et al, 2004). One emerging practical imperative is the geographical expansion of spatial data infrastructures to better provide relevant coastal information for regional ocean governance (Wright *et al*. 2010). For the case described here, regional integration of information on West Indian Ocean reef islands would align the information provided with regional research and management organisations such as the West Indian Ocean Marine Science Association.

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